THE RELATION OF LABORATORY INVESTIGATION TO ASTROPHYSICAL RESEARCH.

By Arthur S. King.

To those working in the relatively young subject of astrophysics, it has been clear from the first that conclusions as to the physical state of the heavenly bodies must be based on the observation of what happens under controlled conditions in our laboratories. Thus in the observatories in which the earlier work in this branch of astronomy was done, such as those of Lockyer and Huggins in London, the apparatus for physical investigation formed a large part of the equipment; and the rapid growth of astrophysics has caused a constantly increasing demand for specialized laboratory work. By this is not meant the use of physical apparatus, of more or less standard form, in connection with astronomical instruments, tho the number of such applications is very large. These uses range from thermostat control in a stellar spectrograph to the measurement of the light from a star by means of a selenium or photo-electric cell, or of its heat by a thermopile. The investigation of solar radiation by the Smithsonian Astrophysical Observatory is largely with physical apparatus. The polarizing instruments used in the study of the Sun's magnetic phenomena are taken from the laboratory, as are the light sources used for comparison spectra with solar and stellar spectrographs. It is rather the regular physical investigations, planned so that their results will apply in the solution of the problems of astrophysics, of which a discussion will be attempted in this article.

The invention of the spectroscope made possible the study of the constitution and physical state of the Sun and stars. The use of this instrument in its many forms in the laboratory has developed the branch of physics known as spectroscopy. The astronomical and the physical lines of work have constantly supported each other, the requirements of astronomy acting as a great stimulus to the improvement of spectroscopic instruments and methods, while spectroscopists have tried whenever possible to apply their results to the

solution of astronomical problems. The early workers found a large field in the identification of the chemical elements in the celestial bodies by means of the correspondence of their spectrum lines with those of known elements in the laboratory. This is the spectrum analysis of the stars, and the requirements of greater accuracy had much to do with the development of spectrographs of high dispersion, of which the most striking examples are perhaps the concave grating of Rowland, which he used in the mapping of the solar spectrum, and the large-scale spectrographs used in the study of the Sun on Mount Wilson. While the possibilities in the identification of spectrum lines may seem to be largely exhausted, this is still by no means an unimportant branch of the work, and any promising lead is at once followed up. The attitude of the workers is similar to that of the chemist, who is always ready to digress from the investigation in hand if an opportunity offers to isolate a new element.

Among the fruitful pieces of work of this kind during the past decade may be mentioned the identification in the spectra of sun-spots of several banded spectra of compounds, which, not being found in the spectrum of the disk, also furnish evidence of a reduced temperature of the sun-spot vapors. One of these banded spectra, which has been shown conclusively by investigations with the arc and electric furnace to belong to titanium oxide, is also the strongest evidence of the presence of oxygen in the Sun. The presence of lithium in the Sun has also been recently established by the correspondence of a sun-spot line with the red line of this element.

At present it would seem that further progress in determining the origin of unknown lines in solar and stellar spectra demands powerful equipment on the laboratory side, in light sources or analyzing apparatus, or both. It was skillful manipulation of a difficult vacuum-tube discharge that enabled Fowler in 1912 to photograph, in a mixture of hydrogen and helium, a series of lines long known to exist in certain stars and ascribed to an unknown spectrum of hydrogen, since the arrangement of the lines was expressed by a formula differing by a constant from the series of hydrogen lines. It is still an open question whether the presence of helium

enables hydrogen to emit these lines, or whether they are due to helium itself under special conditions. After describing these experiments, Fowler expresses this opinion: "The production of the new lines gives a further indication of the probability that there are no special kinds of matter in celestial bodies, and that most, if not all, of the celestial spectra are well within range of laboratory experiments."

But spectroscopy has progressed far beyond spectrum analysis. It now includes the study of the properties and physical states of matter thru the agency of radiation. The early observers of stellar spectra soon perceived variations in the spectra of known elements in different stars. One type of star would show a certain magnesium line very strong; in others, particular groups of iron or titanium lines would show high intensity. A comparison with the behavior of these lines when produced by the arc or spark in the laboratory led to conclusions as to the state of the stars, especially with regard to temperature. The field has been greatly extended. The later study of laboratory spectroscopy has shown a great variety of means of modifying spectra according to the condition of the radiating source. These changes sometimes give a much altered appearance to the spectrum as a whole, owing to a certain set of lines dominating the spectrum when produced in a given way, while they are absent from the same sort of vapor when excited in a different manner. The structure of individual lines is very sensitive to variations in the light source. Such changes may be a widening of the line, perhaps unsymmetrical or accompanied by "reversal" when cooler vapor absorbs part of the light from the widened line; or several lines may appear in place of the original single line, either by the production of satellites or by an actual division of the line into components. The wave-length of spectrum lines may also be altered, very large shifts being produced by high pressure around the source and smaller changes by other causes as yet imperfectly understood.

Observations of celestial spectra often show changes similar to those which we can produce by altering the condition of the light source in the laboratory. We must then attack the problem as to whether we have here the cause of the observed

change in the celestial spectrum. An extended investigation is usually required to show how complete a correspondence exists between the two effects. Exceptions to such a similarity are likely to appear; and it must be considered whether these are real contradictions which would rule out the suspected cause, or differences which might result from recognized conditions in the Sun or stars not to be duplicated in the laboratory. The enormously high temperatures involved, and, especially in the Sun, the differences of level at which the vapors of different elements lie are points to be considered in this connection. Frequently a hypothesis must be abandoned as the result of such an investigation, if negative evidence is clearly developed, but obviously this can be decided only by an experimental test.

A less definite problem and one of great difficulty is the attempt to produce in the laboratory new conditions which will show effects similar to those observed in astronomical work and thus possibly reveal the state of the celestial body. The development of new light sources has been greatly stimulated in this way, and the methods of attack improved. Questions in regard to the state of nebulæ and comets offer a large field, especially in the study of discharges thru gases at low pressures.

Passing to illustrations of the way in which the laboratory may coöperate in astrophysical work, one of the clearest examples is the discovery and further study of the magnetic field in sun-spots thru the correspondence of the phenomena with those of the well-known "Zeeman effect" in the laboratory. Many solar lines had been known to be double in the spot spectrum, while single in the disk. The spectroheliograph showed hydrogen vortices rotating about the spot, and the whirling of charged particles in this way should produce a magnetic field. If such a field were present, the light emitted by the components of the double lines should show polarization. The use of the apparatus commonly employed to detect such effects in the laboratory showed the components of the divided sun-spot lines to be circularly polarized in opposite directions. This, in the light of our present knowledge as to the production of such polarization, demonstrated the exist-

ence of a magnetic field. Further evidence was then sought by determining whether the splitting of sun-spot lines corresponded to that observed for the same lines when the vapor producing them was acted on by a powerful magnetic field. The spectrum of a spark between the poles of an electromagnet showed a close agreement with the spot effects and gave the means of measuring the strength of the magnetic field of the spot.

The main fact of the magnetism of sun-spots being established, much further laboratory study is required in supporting the details of the solar investigation. The magnetic behavior of the elements whose spectra are important in sun-spots needs to be worked out as fully as possible, this often requiring the study of lines whose structure is so complex that they have been omitted in previous work of this kind. With these data available, the magnitude of the effect for different elements in the spot may be considered in connection with level differences as throwing light on the character and form of the spot vortex. Exceptional behavior of certain sun-spot lines with regard to magnitude of magnetic separation and unusual relative intensities of the components require special examination of these lines in the laboratory.

The magnetic field effects in laboratory and spot spectra are illustrated in Plate I. Fig. 1 shows, above and below, the lines in the spark without field, while the inner spectra are from the spark in the magnetic field, given by the light vibrations perpendicular and parallel to the lines of magnetic force, respectively. The wide triplet at the right, having two lines of one polarization and one of the other, may be compared with the solar line in Fig. 2, which shows a similar structure in the spot and changes to a single line above and below in the spectrum of the disk. On each side are seen telluric lines, given by the absorption of the Earth's atmosphere, and naturally unaffected by solar conditions. Nos. 3 and 4 show the effect of the use of a nicol prism and compound quarter-wave plate in the case of triplet lines in the laboratory and in the spot spectrum, the circular polarization of the side components being shown by their alternate extinc-

PLATE I.

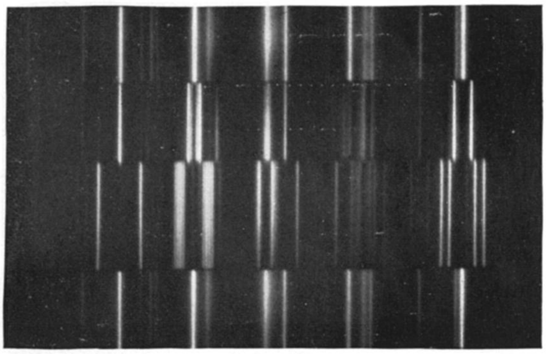

Fig. 1

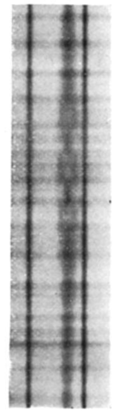

Fig. 2

Fig. 3

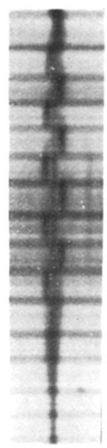

Fig. 4

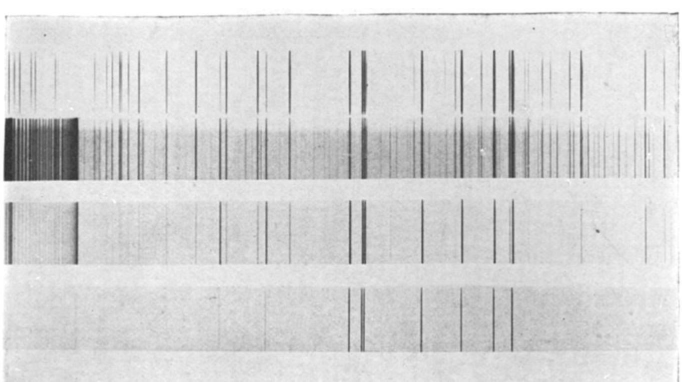

Fig. 5

tion, while the spot line shows also the middle component as a result of the vortex not being viewed axially.

The study of the role of temperature in astrophysical phenomena is another subject requiring constant reference to laboratory observations. We should know (1) the sort of changes that may be due to temperature differences, and (2) what condition, as evidenced by the spectrum, corresponds to a certain temperature stage. A series of light sources is required, covering as large a temperature range as possible. The flame, arc, and spark have been employed, while the electric furnace is a more recent development. In this, metals may be vaporized in a heated carbon tube, the temperature of which can be raised to about 3000° C. Plate I, Fig. 5, shows a portion of the chromium spectrum obtained at three different temperatures of the electric furnace, the top spectrum being that of the chromium arc. A tendency for certain lines to persist with considerable strength at low temperatures is seen. As the temperature rises, the spectrum becomes richer, showing finally the same lines as the arc but retaining distinctive features as regards the relative intensity of lines. The lines strong at low temperature are of special interest by reason of their intensity in sun-spots and in red stars, the evidence of low temperature in these bodies resting largely on this class of lines.

A difficulty arises from the fact that the upper limit of the furnace temperatures is much below the temperatures met with in the Sun and stars. However, the direction and rate of change in the lines of a spectrum produced by rising temperature may be observed, and it is fair to assume that this change, consisting of a strengthening of some lines and a weakening of others, will continue throughout a considerably higher range. The arc and spark, in which the vapor is made to radiate by the passage of an electrical discharge, have been considered, with some reservation, as giving higher steps in the temperature scale. Certain lines which are faint or absent in the furnace spectrum develop to high intensity in the arc, and another group, the "enhanced lines," in the spark. These enhanced lines are notably weaker in sun-spots than in the solar disk, and have been taken to indicate high

temperature when occurring in stellar spectra. Their importance has led to much laboratory investigation as to the conditions required for their production. Just at present a hypothesis receiving attention is that they are due to multiply charged ions which require an intense excitation to cause them to radiate. In general the laboratory sources having violent excitation, such as the disruptive spark, are most favorable for the enhanced lines, but vacuum sources, notably the explosive "tube-arc," using a potential of only a few volts, bring them out strongly, the greater free path of the particles perhaps compensating for the low voltage. The uncertainty regarding the production of enhanced lines shows how far we still are from an intimate knowledge of radiation processes. As the matter stands, we seem justified in assuming that high stellar temperature should produce these lines, tho in the laboratory they must usually be excited by electrical means.

The study of the finer details in spectra made possible, especially in solar work, by high-dispersion instruments, requires support on the laboratory side in the examination of the changes in structure and the widening influences to which individual lines are subject. Causes which are known to act in this way must be examined to see whether the correspondence of effects is such that these causes are probably active in the Sun or stars. The effect of a magnetic field in changing line structure has been described. An analogous effect by an electrical field has recently been discovered by Stark and its action on the lines of various elements is being closely studied in the laboratory. The splitting of the blue hydrogen line in the vacuum tube spectrum is shown in Plate II, Fig. 6, together with an unaffected metallic line. The lines of some elements are much more subject to the effect than others, and this difference among elements as well as the different behavior of various lines must be worked out as fully as possible before we know what astrophysical applications the phenomenon may have. The widening of lines in different electrical sources is probably related to the Stark effect. The different sensitiveness of lines to widening thru changes in vapor density is of interest, as is also the complex structure of lines under ordinary conditions shown

PLATE II.

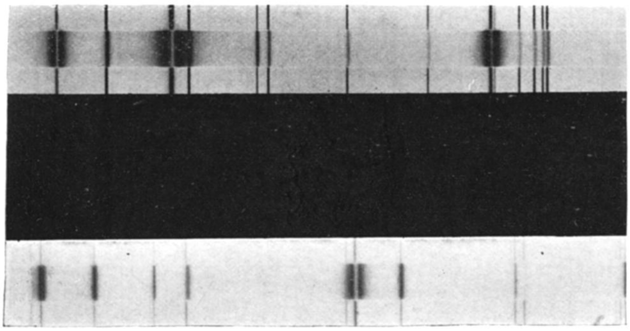

Fig. 7

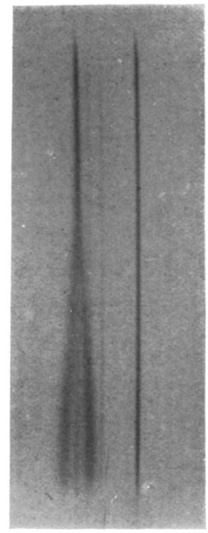

Fig. 6

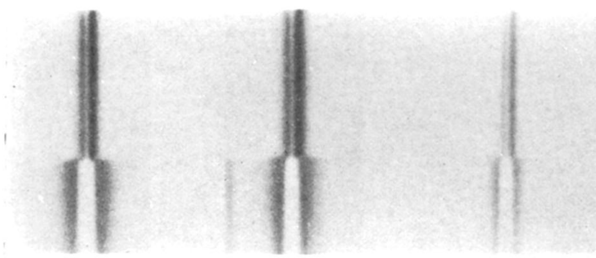

Fig. 8

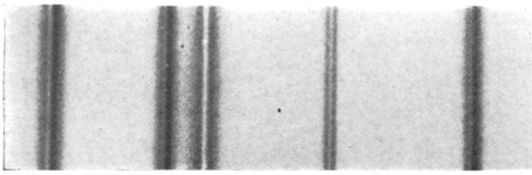

Fig. 9

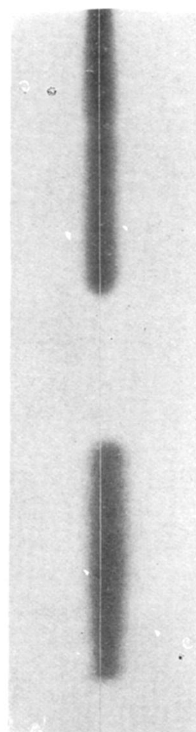

Fig. 10

by high-resolution spectrographs. Thus the fact that λ 4481 of magnesium is made up of two close lines of different intensities probably explains the discordant wave-lengths of this line in stellar spectra.

Displacements of spectrum lines owing to altered conditions of the light-source have interest in astrophysics aside from their physical importance. Small differences are often found between the wave-lengths of corresponding lines in the solar spectrum and in that of the arc. The effect on such lines of the various displacing agencies in the laboratory must be tested to see if any of these causes are probably active in the Sun. The matter is of interest in stellar work also, since there is a possibility that not all of the observed displacements are due to radial velocity.

Increased pressure in the gas surrounding the light source is the best-known method of displacing lines. Plate II, Fig. 7, shows the effect of pressure in the electric furnace upon the iron spectrum, the inner portion of the lines being produced at a pressure 9 atmospheres above that for the outer portions. There are criteria which indicate whether displacements in a celestial spectrum may be due to pressure. The pressure displacement, which can be made very large, is regularly accompanied by decided broadening, and the amount of displacement may be very different for different groups of lines of the same element. A lack of agreement with the solar displacements in these features has made it improbable that any considerable pressure exists in the Sun's photosphere.

Other displacing agencies under investigation are those acting in powerful spark discharges and in the "tube-arc," giving usually an unsymmetrical structure to the lines. In Plate II, Fig. 8, are shown unsymmetrically reversed lines in the spark compared with the same lines symmetrical in the arc, and in Fig. 9, a group of tube-arc lines of different classes, showing symmetrical and unsymmetrical reversals. A further means of displacing lines, probably related to the foregoing, is found in the conditions close to the pole of the arc, where certain lines are found to be displaced, usually toward the red, with respect to their positions in the vapor from the middle of the arc. This "pole-effect" is shown in

Plate II, Fig. 10, where the artificial line indicates the position of the spectrum line emitted by the central vapor. These phenomena are especially important in showing the constancy of wave-length which a line may be expected to maintain, lines strongly subject to such disturbances of position not being suitable for standards in any source.

Among methods of measuring spectra, the interferometer may be mentioned as one whose range of application is increasing. Plate III, Fig. 11, gives the interference pattern presented by the green mercury line, the fainter circles being due to satellites. Let these rings be projected on a slit so that this forms a diameter of the ring system. The image of the slit is then seen to be crossed by a series of maxima due to the intersections with the rings. If the slit is part of a grating spectrograph free from astigmatism and is illuminated by an iron arc, the spectrum has the appearance seen in Fig. 12, of Plate III, each image of the slit consisting of a series of maxima whose distances apart vary with the wave-length. The relative wave-lengths are determined by measuring the diameters of the ring systems for the different lines and may be compared with the system produced by a standard line, such as the red line of cadmium, from light reflected into the same optical system. In this way a high order of accuracy for the wave-lengths is obtained. In the laboratory of the Mount Wilson Solar Observatory, measurements are being made in this way of the sharp lines produced by the iron arc when operated in a partial vacuum. A similar arc will then be used on Mount Wilson to give standard lines for the measurement of solar wave-lengths, based on the laboratory values. The method promises to be of service in many problems.

The testing of an astrophysical hypothesis by laboratory methods is illustrated by a recent investigation of anomalous dispersion effects with the electric furnace. According to theory, it appeared possible that certain distributions of the vapor masses in the Sun might cause mutual displacements for pairs of lines of nearly the same wave-length when emitted by those vapors. The furnace was arranged to imitate such a distribution, and favorably situated lines were measured,

PLATE III.

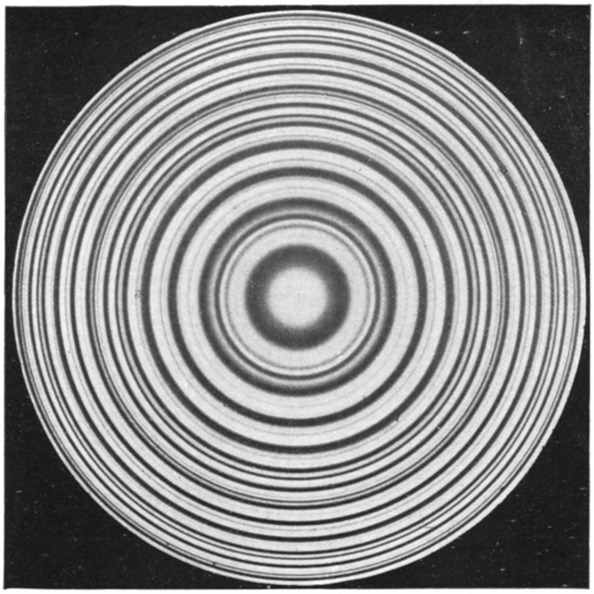

Fig. 11

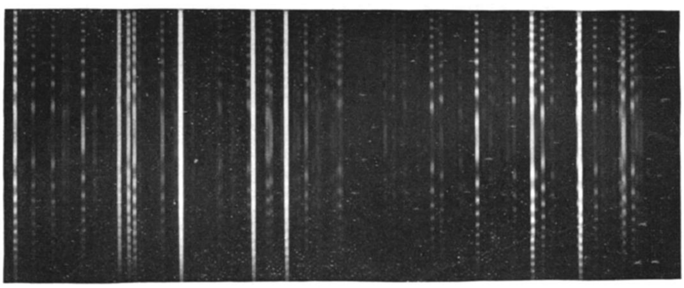

Fig. 12

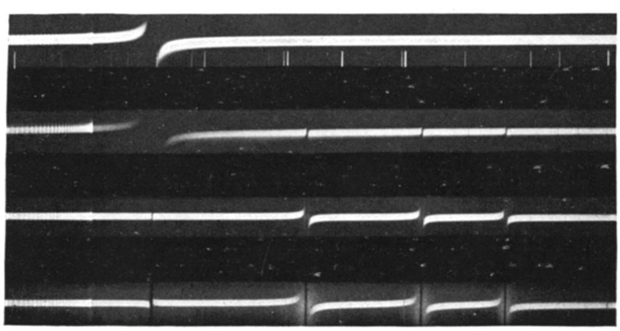

Fig. 13

no evidence being found of the suspected effect. Much additional material has been collected with regard to the degree to which various lines are subject to anomalous dispersion and the conditions of the vapor which govern the effect. The anomalous dispersion exhibited by three chromium lines and by the blue line of calcium at different temperatures is shown in Plate III, Fig. 13.

Laboratory studies in connection with astronomy are not confined to spectroscopy, tho naturally this is the major part of the work. A great variety of experimental tests may be required, involving many branches of physics and chemistry. Extended observations have been made in the Mount Wilson laboratory on the phenomena of vortex motion in liquids and vapors, with reference to the character of solar vortices and the formation of sun-spots. Special attention was paid to the imitation of bipolar sun-spots, when a vortex is made to curve under the surface, exposing the oppositely rotating ends. Experiments on the ionization of gases have also been carried out to test certain assumptions as to solar conditions.

The effort has been made, since the foundation of this observatory, to maintain a suitable laboratory for the regular investigation of physical problems related to the astronomical work. Many laboratories, especially those connected with universities, are equipped to carry on such investigations to a greater or less extent. Much work of the highest value has been done in such laboratories and the contributions of the workers so engaged are very important. Greater continuity in the prosecution of extensive pieces of research, however, is possible in laboratories specially equipped and with a staff having full time for these problems. If such a laboratory can be an integral part of an observatory, the resulting close coöperation will add much to the general effectiveness of the work.

Mount Wilson Solar Observatory,
January 10, 1917.

Titles for Plates.

Plate I

1. Effect of magnetic field upon spectrum of electric spark.
2. Magnetic separation of sun-spot line.
3. Alternate extinction of side components of a magnetic triplet in spark spectrum.
4. Corresponding effect for sun-spot line with same apparatus.
5. Spectrum of chromium in arc and at three temperatures of electric furnace.

Plate II

1. (6) Effect of electric field on blue hydrogen line.
2. (7) Displacement of electric furnace lines by pressure.
3. (8) Unsymmetrically reversed lines in spark spectrum.
4. (9) Symmetrical and unsymmetrical reversals of tube-arc lines.
5. (10) Displacement of line near pole of iron arc.

Plate III

1. (11) Interference rings given by green mercury line.
2. (12) Iron lines given by interferometer combined with grating spectrograph.
3. (13) Anomalous dispersion shown by calcium line *g* and three chromium lines at different temperatures.